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Using Smartphones to Innovate Laboratories in Introductory Physics Courses

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Abstract. The *SmartPhysics* project involved two higher education institutions, one in Italy and one in the US, with the aim of exploring the use of smartphones for laboratory experiments in introductory Physics courses. Here we present and discuss two experiments that were developed in the project: the pendulum experiment, consisting in the measurement of the gravitational constant using a proximity stopwatch, and the 'bouncing ball' experiment, aimed at measuring the energy lost in inelastic collisions with a hard surface. Both experiments were tested with the students in the academic year 2021-22. Our results and didactical reflections contain suggestions for the use of smartphone-based experiments in university settings, in comparison with traditional experiments and considering the specificities of different contexts.

1. Introduction

During the 2020 lockdown, schools and universities were challenged by the problem of organizing remote laboratory sessions. This experience motivated higher education institutions to revise their curricula by incorporating new technologies and to explore their benefits beyond the emergency period [1,2]. One of the explored solutions was to take advantage of the sensors contained in smartphones (e.g., accelerometers, sound meters, gyroscopes, barometers, magnetometers, and proximity sensors) made available through specifically developed apps [3,4].

The *SmartPhysics* project was developed by a team of physics faculty and physics education researchers at the University of Padua (UniPD) and the City University of New York (CUNY). The goal of the initiative was to pilot the process of revising and innovating introductory physics laboratories for undergraduate Science and Engineering courses. The explored innovation was the development and testing of smartphone-based experiments, including documentation to be shared with instructors. Our research question regarded the affordances and challenges of smartphone-based experiments in first-year physics courses for non-Physics majors. In this contribution we describe the development and pilot testing of two of these experiments: the 'pendulum experiment', developed at UniPD, and the 'bouncing ball experiment', developed at CUNY.

2. Methodology

The project started in September 2021 with the goal of testing the experiments in general physics courses in the 2022 Spring term. The team involved in the project was composed of physics faculty, researchers in physics education, teaching assistants and student tutors.

PhyPhox [5,6] is the mobile application chosen for the project. Well-known in the physics education community, this app was developed at Aachen University with the aim of making smartphone sensors easily accessible to the user. PhyPhox is free, user-friendly, available for all mobile systems, and it offers the possibility to visualize, export and share the collected data. It also allows a second device to be connected to manage remote data acquisition and to visualize the collected data, a feature that is particularly useful when the smartphone itself is used as part of the setup. PhyPhox is also linked to a community of people that collaborate to improve the experiments.

The project was developed in two phases: Phase 1 (Sep 2021-Jan 2022) included the testing and feasibility evaluation of different experiments, while Phase 2 (Feb-May 2022) was dedicated to the pilot testing of the experiments in the instructors' courses. In Phase 1, after a common training session, researchers at both institutions worked independently on different experiments, sharing the methodology and updates on the ongoing testing. At the end of this phase, researchers regrouped to discuss the results and to select the experiments to be included in the pilot trial. Implementation then proceeded according to each institution's schedule, and the results were shared and discussed at a final meeting in June 2022.

Initially, we identified several experiments that could be of interest to first-year physics courses. These included experiments for which traditional laboratory materials already existed and experiments that are not traditionally taught due to limited materials or lack of resources. We compiled an initial list of experiments that could be implemented with PhyPhox and we tested them (see table 1).

Table 1. The experiments tested in the initial phase of the *SmartPhysics* project. The ones that were further developed for use with the students are marked in with a star (*).

Experiment	Short description	Sensor
Roll	The distance Δx rolled by a cylinder within Δt is computed from the velocity v(t) of the cylinder. v(t) is calculated from $\omega(t)$	Gyroscope
Pendulum* (proximity stopwatch)	The phone records the motion of a pendulum swinging above it. The value of g is computed from the measured period T	Proximity stopwatch
Pendulum (accelerometer)	The smartphone itself acts as the pendulum. The value of g is computed from the pendulum's angular velocity through $\omega^2 = g/L$	Gyroscope and Accelerometer
Doppler effect	The speed of sound is computed from the Doppler effect formula. We combined the Doppler experiment with the pendulum setup.	Frequency sensor
Speed of sound	Two smartphones located at a known distance allow to measure the speed of sound as a signal that travels from one phone to the other.	Acoustic stopwatch
Free fall	The time interval Δt is measured using an exploding balloon that releases the mass and the noise of the impact with the floor.	Acoustic stopwatch
Inelastic Collisions of a Bouncing Ball*	The time of each bounce is recorded and used to determine the highest points in the trajectory of the ball in between collisions, i.e. the potential energy, and therefore the energy lost at each bounce.	Acoustic stopwatch

From this set, after a common discussion we decided to focus on two experiments, one at each institution. At UniPD, the 'pendulum (proximity stopwatch)' experiment was chosen, while at CUNY the choice fell on the 'bouncing ball' experiment. The selection criteria were as follows: the required sensor should be available in all types of smartphones; the experiment should offer an interesting data analysis part; the experiment should allow obtaining a reasonably accurate and precise result.

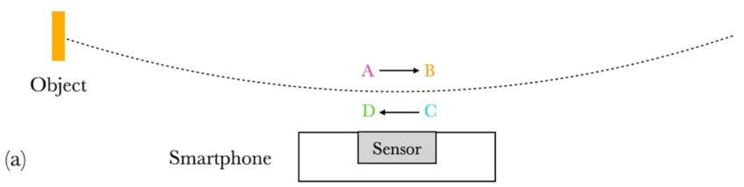
3. The pendulum (proximity stopwatch) experiment

The goal of the pendulum experiment is to obtain the value of the gravitational acceleration, g, from the measurement of the period T of a simple pendulum, through the well-known relationship:

$$T = 2\pi\sqrt{\frac{L}{g}} \tag{1}$$

where L is the length of the pendulum. This is a standard experiment used in first-year physics courses. To measure T, we used the smartphone's proximity stopwatch available through PhyPhox. The sensor is activated as an object gets closer to it than a trigger distance ("trigger below", user-defined in the app settings) and is deactivated as the object gets farther than threshold; a typical "trigger below" distance is 5-10 cm. The phone records binary data in terms of activations and deactivations of the sensor, rather than a continuous value for distance. More specifically, when the sensor is activated, it records a "0" value (object "close") and gives the corresponding detection time. When it is deactivated, it records a positive integer number the value of which depends on the phone, here "5 cm" (object "far"), and the corresponding time.

In the experiment, a small, massive object hanging from the end of a string (the pendulum) swings over the phone. The phone's position is adjusted so that the pendulum gets close enough to activate the sensor in the lowermost part of its trajectory. The (de)activations of the sensor during a single oscillation are represented schematically in figure 1. The point where the sensor is first activated is marked with A; continuing its oscillation, the pendulum moves away from the sensor and thus deactivates it (point B). The pendulum then oscillates back and activates/deactivates the sensor again (points C and D). As a new oscillation starts, this sequence of activations/deactivations is repeated. The period of the oscillation can be estimated by calculating the time interval between two corresponding flags, e.g. between two activations at point A (figure 1c). After the oscillation plane is stable, the experiment is run for 5 minutes (100 oscillations). To calculate g, we select the data interval in which the period remains constant, and we average over all the oscillations and pairs of corresponding points (4 pairs for each oscillation, resulting in 400 points).



(b)

Time (s)	Distance (cm)	
3.147183292	0	A
3.265280375	5	B
4.299937458	0	C
4.419877917	5	D
5.636475375	0	A

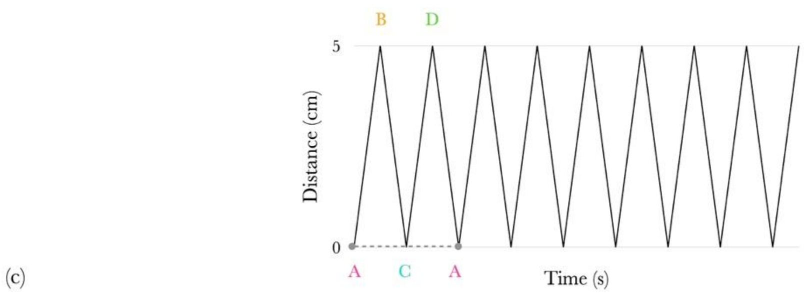


Figure 1. (a) A scheme of the pendulum experiment. (b) An excerpt of raw data from a sample experiment. (c) A typical illuminance-time graph obtained from the experiment. The five points reported in the table are marked with the same letters. The period of the oscillation is calculated as the time difference between two corresponding flags.

3.1. Pilot experiment

In the Fall semester of 2021, we conducted a pilot experiment with a class of 70 first-year students enrolled in the Environmental Science and Technology degree program. We collected data from all the valid experiments, eliminated outliers (values that differ by more than two standard deviations from the median of the sample; points with an error larger than two standard deviations from the median of the errors) and estimated the best value of *g* by averaging over all data sets. The estimate obtained was $g = (9.84 \pm 0.08)$ m/s^2 (figure 2). The known value for Padua is 9.806450 m/s^2 (from *Physikalisch-Technische Bundesanstalt*, Germany).

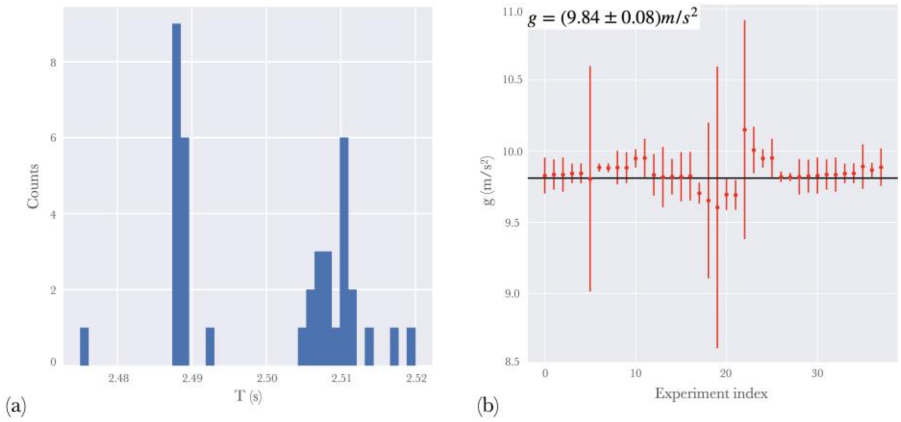


Figure 2. Data from the pilot experiment proposed in Fall 2021. (a) Values of T measured from different student groups. The double-peaked distribution reflects human errors in the estimation of the length of the pendulum, the distribution of which is also double-peaked (not shown). (b) Estimated values of g for each experiment, after data cleaning. The black line is the known value of g for Padua.

To evaluate the experiment and improve it for the second semester, we collected student feedback (figure 3 on the next page). Students found the experiment interesting, also in terms of discovering new ways to employ their smartphone. Using the app was easy for them, while they found it more challenging to download the data and perform the analysis. In fact, the experiment provides a large data set that needs some interpretation and elaboration. Although instructors considered this to be an opportunity for the students, this feedback indicated that students needed more scaffolding as they were dealing with such type of data for the first time.

3.2. Second iteration in Spring 2022

The experiment was proposed again to 300 first-year students in two Engineering courses in the Spring semester of 2022. Based on student feedback from the pilot experiment, the TAs produced video tutorials to support the setup of the experiment, data collection and analysis. This time, students collected data for different lengths (10 different lengths for course A and 5 different lengths for course B); the best estimate of g was evaluated using both weighted mean and the least squares method. Again, to calculate the best value of g, we averaged data from all the students' experiments. Examples of students' data are shown in figure 4.

At the end of the pilot utilization in the courses, the instructors discussed the pros and cons of the smartphone-based experiment compared to its traditional companion method. Some pros are automatic data acquisition (each oscillation is measured four times, whereas in the standard experiment, students take a measurement every 10 oscillations), which dramatically increases the number of measurements; a large data set in a standard format is obtained, which can be easily exported, shared and/or integrated

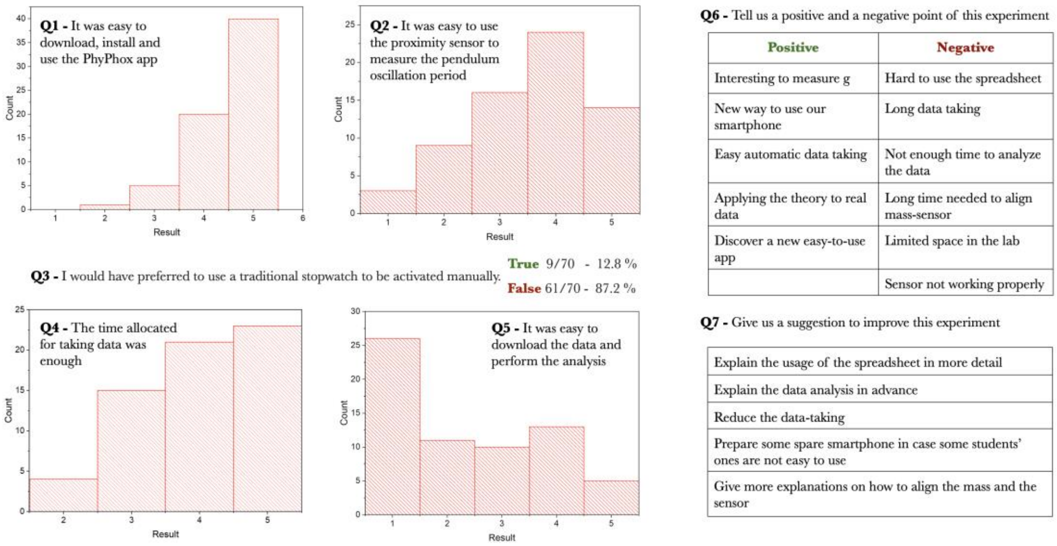


Figure 3. Students' feedback from the pilot experiment.

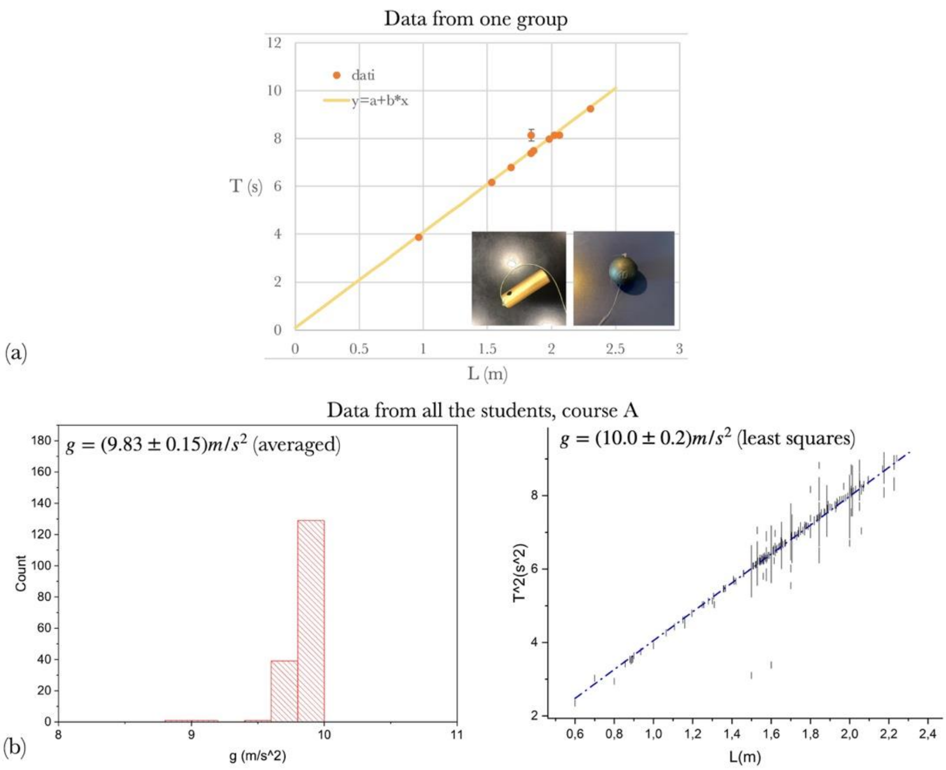


Figure 4. Example of students' data from the experimentation in the second semester (Spring 2022). (a) Data from one group of students; (b) Data from the whole class and the corresponding estimation of *g*.

with more data (e.g. data from other students' experiments, expanding opportunities to discuss data analysis). The cons are that students have less control on the data: there is a risk that they pay less attention to the data they obtain, leading to some nonphysical periods and/or large errors. There were issues with some types of smartphones, even though working in groups partially solved the problem. Another possible drawback is that students spent more time analyzing the data and less time optimizing the setup with respect to the traditional experiment, whereas the latter aspect is important for first-year students who are learning how to best run an experiment. The TA tutorials have been helpful in this regard, helping students get through the technical part of data analysis more easily. We believe that the smartphone-based approach can definitely be introduced for home experiments and/or for exploring new setups, while if a higher quality of the experiment is desired, more accurate equipment should be chosen.

4. The bouncing ball experiment

4.1. The experiment

The purpose of this experiment is to measure the energy lost by a bouncing ball going through a series of inelastic collisions with a hard surface. While many laboratory activities in the General Physics curriculum focus on energy conservation, i.e., the conservation of potential energy into kinetic energy in the free fall of an object, the goal this experience is to quantify energy dissipation. To achieve this goal, the identified strategy was to perform a series of measurements of the energy of the system as a function of time so that we can chart and plot the decrease in the mechanical energy of the system.

To collect the data, we employed the smartphone's acoustic stopwatch through PhyPhox. The tool utilizes the smartphone microphone to record sound events caused by some action. Using the sound emitted each time that the ball hits the surface, the acoustic stopwatch allows the user to measure the time intervals between collisions and transfers them to a spreadsheet for further analysis. We note here that the PhyPhox app also contains a built-in experiment, called "Inelastic Collision", which processes the data to provide an immediate result for the problem at hand. While this could be an interesting option for introductory courses directed to non-STEM majors, for our intended learning goals we decided to develop an experimental activity that only relies on the raw data provided by the acoustic stopwatch.

In the experiment, we assume that the surface against which the ball bounces can be considered at rest during the collision (therefore simply tracking the change in kinetic energy of the ball before and after the collision), and that in between two consecutive collisions the bouncing ball is in free fall and therefore its energy is conserved. In first approximation, we therefore neglect air resistance and any other force that might act on the system between consecutive collisions.

With these approximations, we can easily get a measure of the total energy of the system in between two consecutive collisions. In fact, at the highest point in the trajectory of the ball, the total energy of the system corresponds to its potential energy, which can be estimated by measuring the maximum height reached by the ball with respect to the ground, H. It is straightforward to compute H from gravitational acceleration g and the time t it takes to the ball to get to H from the ground:

$$H = \frac{1}{2} g t^2 \tag{2}$$

The time t in equation (2) is half of the interval between two consecutive collisions, which is measured by the acoustic stopwatch.

Repeating the measurement for subsequent bounces, we can finally calculate the fraction of energy lost in each bounce. In particular, for each bounce we can chart the total energy E_i as a function of time and then proceed to compute the fraction of energy dissipated at each bounce, $\{\%E\}_i$, and the coefficient of restitution of the collision $\{C_R\}_i = \left|\frac{v_i}{v_{i-1}}\right|$ from:

$$\{\%E\}_i = 1 - \frac{H_i}{H_{i-1}} \tag{3}$$

$$\{C_R^2\}_i = \frac{H_i}{H_{i-1}} \tag{4}$$

The results can be plotted and the obtained graphs can be analyzed to get a better grasp of the behavior of the system.

4.2. Didactical use and reflections

As part of the pilot project, the lab was tested at CUNY during the Spring semester of 2022 in two different settings: the General Physics laboratory at the *New York City College of Technology* (24 first-year students, mostly enrolled in Engineering and Architecture Technology Bachelor Programs) and the University Physics course at the *Borough of Manhattan Community College* (25 students, enrolled in an Associate Degree in Computer Science).

The activity was performed with different sets of balls (a metallic ball, a hard plastic ball, and a ping-pong ball) released from the height of about 1 meter over the hard surface of the laboratory desks. An Excel workbook was provided to scaffold and guide students' work: figure 5 shows a sample of the obtained data and graphs for the case of the ping-pong ball.

Section 1. Collecting DATA

Initial Height (m)	
h0	1.00

Mass of the Ball (g)	
M	0.04

Time Collisions (s)	
t1	2.03533
t2	2.77935
t3	3.41700
t4	3.97350
t5	4.46854
t6	4.91794
t7	5.32671

Section 2. Data Analysis: Height and Energy

Time Interval (sec)	Height (m)	Energy (J)
-	1.00	0.392
0.74402	0.679	0.266
0.63765	0.499	0.195
0.55650	0.380	0.149
0.49504	0.301	0.118
0.44940	0.248	0.097
0.40877	0.205	0.080

Section 2. Energy Loss and Coefficient of Restitution

Bounce Number	Energy Lost	Coefficent Rest.
1	32.1%	0.824
2	26.6%	0.857
3	23.8%	0.873
4	20.9%	0.890
5	17.6%	0.908
6	17.3%	0.910

Section 3. Plotting Data

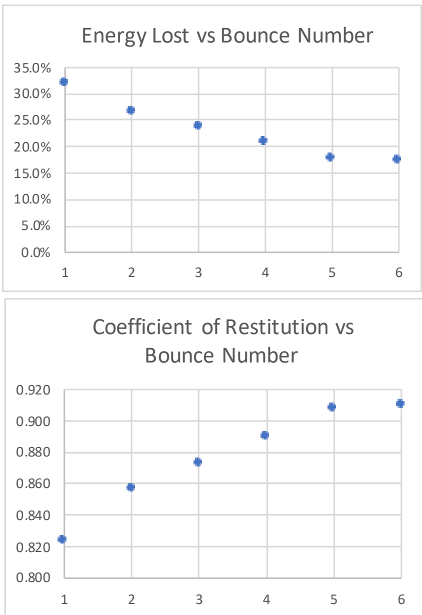


Figure 5. Example of students' data from the bouncing ball experiment (Spring 2022). Data are collected (a), analysed (b) and plotted (c) by populating an Excel workbook which was provided at the beginning of the activity.

To engage students in reflection about the experiment and to stir a class discussion, guiding questions were used, leading to further conjectures and possibly to a deeper understanding of the physics problem.

- [Assumptions] *How many assumptions did we make in out derivation? Can you list them all? What would be the consequences of relaxing some of these assumptions?*
- [Elastic vs inelastic collisions]. *Is energy conserved? If you performed the experiment with different balls, which ones are dissipating more energy? Why so?*
- [Uncertainties] *How can we estimate error bars? What would be a simple way of including an uncertainty on our data?*

- [Fitting the curves] *What kind of mathematical behavior do you observe in the plots? Which functions could we use to fit the data?*
- [Comparing different balls] *How can we compare the elasticity of different bouncing balls? What are the parameters that best define the "amount of elasticity"?*
- [Coefficient of restitution] *What are the features of the system that affect this quantity? Is the coefficient of restitution constant? Why so?*

To assess students' work, a list of learning outcomes (LOs) for the laboratory activity were identified, targeting different aspects of student development:

- [LO1] *Understanding of the qualitative and quantitative differences between an elastic and an inelastic collision*. This LO is related with the understanding of the physical concepts behind the experiment, namely the (non-)conservation of energy. By observing the ball bouncing lower and lower after each collision, students should visualize and experimentally test the statements and definitions contained in the physics textbook.
- [LO2] *Developing technical abilities in organizing, charting, plotting, and analyzing data.* The second LO addresses scientific abilities [7] and in particular the ability of collecting, organizing, and manipulating data.
- [LO3] *Understanding of the role of experimental data in scientific inquiry and awareness of the effect of assumptions and biases in their interpretation.* The third LO is about critical thinking and achieving a deeper understanding of the scientific process. Formulating hypotheses and validating (or rejecting) them through the observation is the main focus of this portion of the assessment.

A scoring rubric with three levels (proficient – 3 points, satisfactory – 2 points, developing – 0/1 points) was developed for each LO and used for assessing students' work (see figure 6).

Scoring Rubric - Inelastic Collision of a Bouncing Ball

Student Name ____________ Total ____

Learning Outcome	*Proficient (3 points)*	*Satisfactory (2 points)*	*Developing (0-1 points)*	*Score*	*Notes*
LO#1: Understanding of the qualitative and quantitative differences between an elastic and an inelastic collisions.	The students shows a clear understanding of the problem, provides correct examples of both kinds of collisions, and is able to explain the topics to other students (both in oral and written form).	The students has a general understanding of the problem, but not a solid grasp on consequences and applications.	The students is still confused about the topics and cannot describe (either in words or in writing) a consisted definition of the two kinds of collisions.		
LO#2: Developing technical abilities in organizing, charting, plotting, and analyzing data.	Data is neatly organized in the tables. Accurate work in plotting and interpreting the results, with rare errors or omissions.	The collected data is not clearly organized. Minor errors or omissions in recording and organizing data, creating plots, interpreting plots, answering questions using data.	Data are missing or organized in a sloppy manner. Major errors or omissions in recording and organizing data, creating plots, interpreting plots, answering questions using data.		
LO#3: Understanding of the role of experimental data in the scientific inquiry. Awareness of the effect of assumptions and biases in their interpretation.	Clear understanding of the difference between experimental data and theoretical formulas. Awareness of assumtions and limitations contained in the formulas, and of biases and error uncertainties that might affect the data.	The students is able to compare the data with the formulas and make some general conclusions and remarks, however does not have clear understanding of assumptions and approximations, as well as error uncertainties.	Students is confused about several aspects of the scientific inquiry, either about assumptions in the theroretical derivations or related with error analyses. They follow procedures without grasping the actual reasons behind them.		

Figure 6. Scoring rubric for the bouncing ball experiment (Spring 2022).

We conclude this section by providing further suggestions on how we can differentiate the the experiment according to the level of complexity of the class, and the previous preparation of the students.

- *Non-STEM intro class*: no further analyses, just qualitative discussion. For short labs, using the "Inelastic Collision" app instead of collecting raw data with the acoustic stopwatch.

- *Intro class, mixed audience*: no further analyses, use raw data and get all the way to the plots. Discussion as deemed appropriate by instructor.
- *Science non-physics major*: Use the plots as a starting point for discussion and modeling of the system as discussed above. Can we fit energy vs time? Which curve would best fit the data?
- *Physics major*: In addition to question listed above, go deeper on the analyses of elasticity. Why does C_R increase? Also, can we predict the initial height H_0 of the ball from the data?

As a final remark, these activities are well suited to be performed in a traditional laboratory classroom as well as in a remote setting. The equipment needed is indeed minimal: simply a measuring tape and a ping-pong ball (or any other ball that produces a loud sound at impact with a surface). Moreover, the measuring procedure can be easily handled by a single person.

5. Conclusions

Our results suggest that smartphone-based laboratory experiences can be successfully used in introductory physics experiences, even in university settings. However, it is critical to reflect on the support to be provided to the students and on the instructional actions to be put in place in order to achieve the desired learning outcomes. We will continue to test these and more smartphone-based experiments in physics courses and, at the same time, deepen our reflection on the scientific abilities that can be developed through these experiments, in comparison with their traditional companion methods or as new possibilities to enrich the landscape of educational laboratories.

Acknowledgments

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